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COHERENT at the Spallation Neutron Source

Robert L. Cooper
New Mexico State University
on behalf of the COHERENT Collaboration

Outline

- Physics Motivation for Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- How to measure CEνNS
  - Production of neutrinos at SNS
  - Detection with multiple technologies
  - Suppression of background neutrons

- Status of COHERENT and other activities

"Wait a minute! Isn't anyone here a real sheep?"

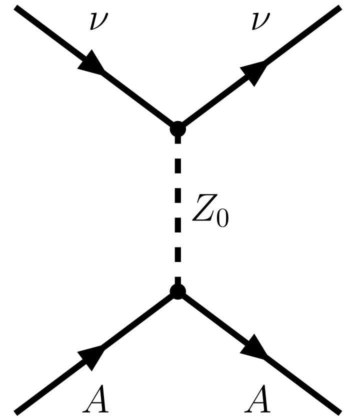
CEνNS (pronounced sevens)

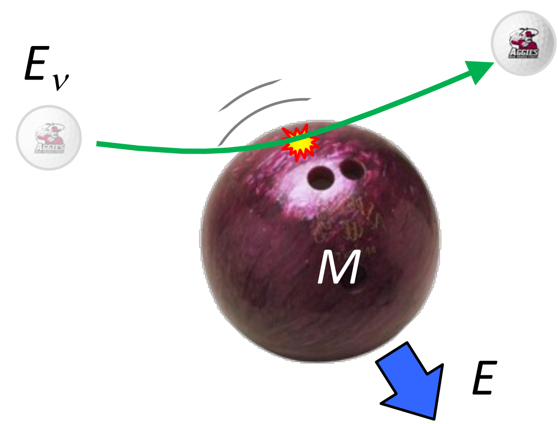
- Coherent Elastic Neutrino-Nucleus Scattering
- Flavor blind Neutral Current process that scatters the entire nucleus as a whole
- To probe a “large” nucleus (few × 10^{-15} m)

$$E_\nu \lesssim \frac{hc}{R_N} \cong 50\ \mathrm{MeV}$$

- Recoiling nucleus is detection signature

$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50\ \mathrm{keV}$$





PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

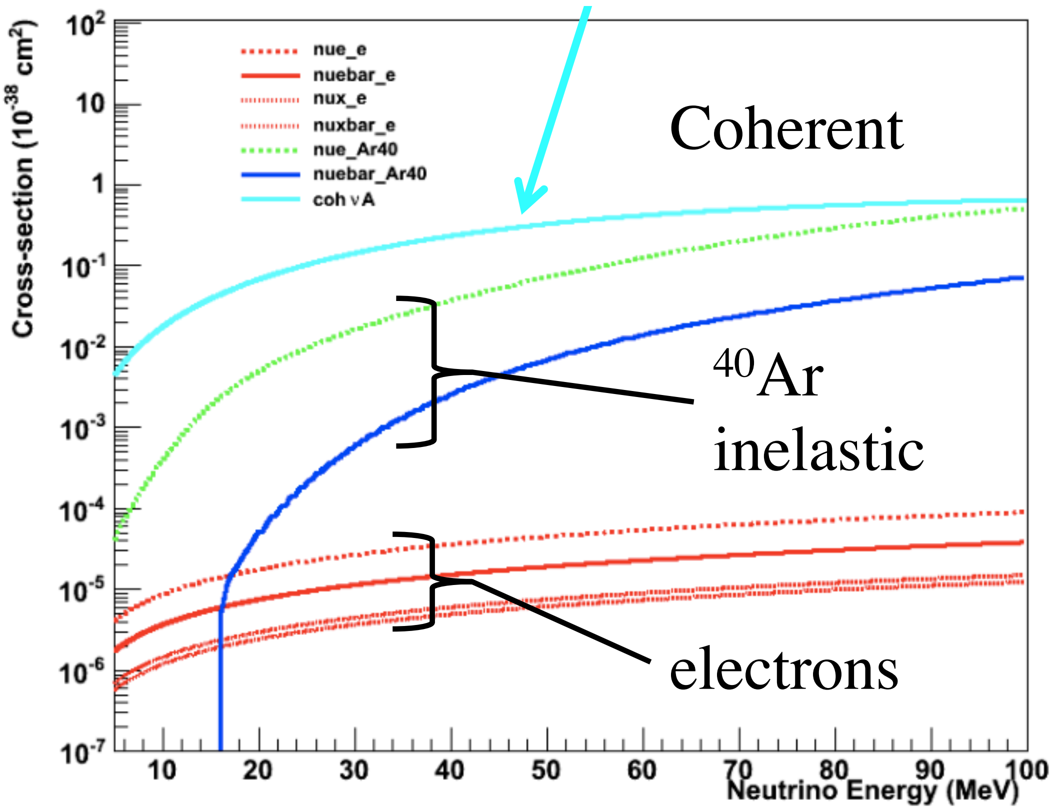
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

CEνNS Cross Section

- CEnNS is the dominant cross section at low neutrino energy
- As neutrino energy increases, incoherent processes increase
- Total coherent cross section is linear in neutrino energy at low energy

ν Cross Section vs. Energy



Structure CEνNS Signal

- Standard Model Prediction

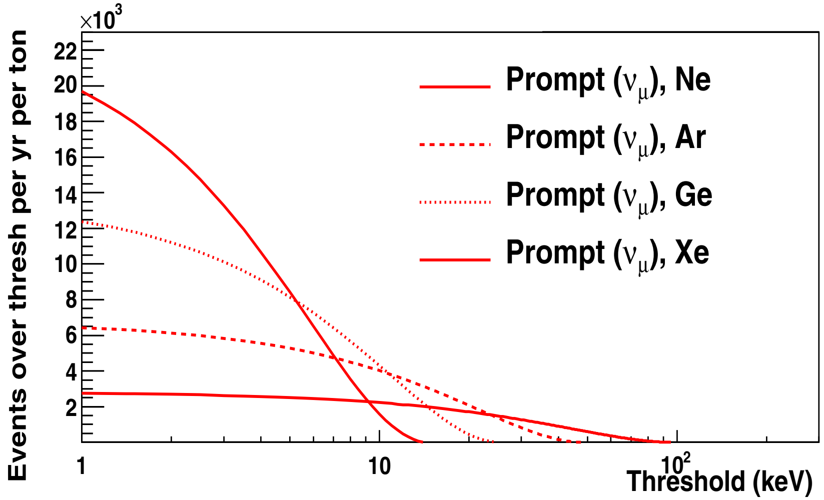
$$\frac{d\sigma}{dE} = \frac{G_F^2}{4\pi}\left[(1-4\sin^2\theta_w)Z - N\right]^2 M\left(1-\frac{ME}{2E_\nu^2}\right)F(Q^2)^2$$

≈ 0 → protons have small effect

square of sum → part of coherence condition

nuclear form factor → distribution of neutrons

Detection Rate [ton^{-1} year^{-1}][1]

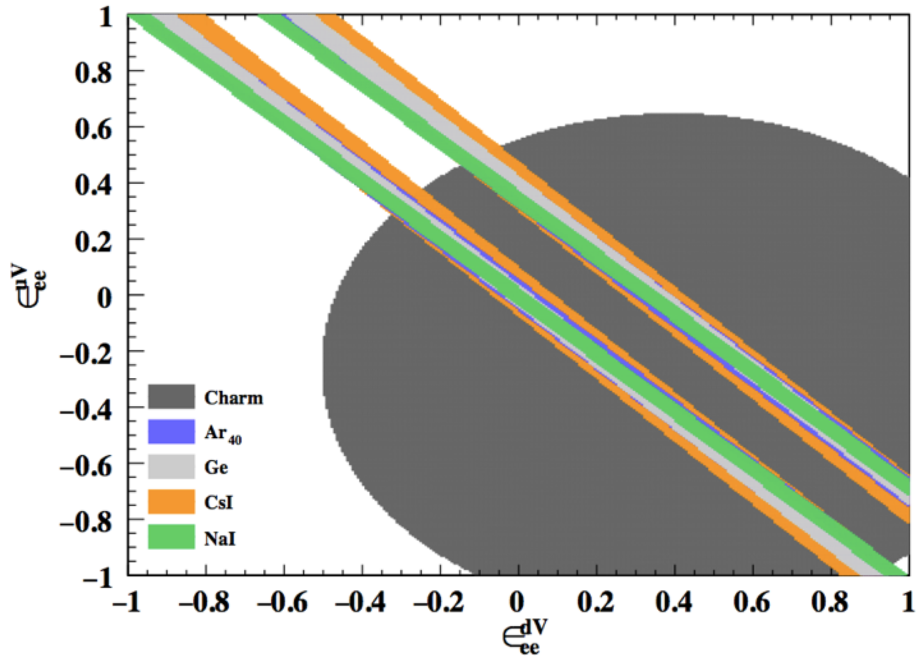


- Recoil energy (M^{-1}) and rate (N^2)

[1] K. Scholberg, *Phys. Rev.* **D73** (2006) 033005. arXiv:hep-ex/0511042.

Physics Motivations for CEνNS

- Non-Standard Interactions
- Multiple targets can greatly improve CHARM experiment limits on NSI
- Meaningful limits can be set with first generation experiments
- NSI may have significant influence in DUNE CP-violation search[1]



$$\mathcal{L}_{\nu H}^{NSI} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon_{\alpha\beta}^{qL}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon_{\alpha\beta}^{qR}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

(Plot) K. Scholberg, *Phys. Rev.* **D73** (2006) 033005. arXiv:hep-ex/0511042.
[1]M. Masud, A. Chatterjee, P. Mehta, arXiv:1510.08261 [hep-ph].

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TABLE I. Constraints on NSI parameters, from Ref. [35].

NSI parameter limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \rightarrow e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \rightarrow e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

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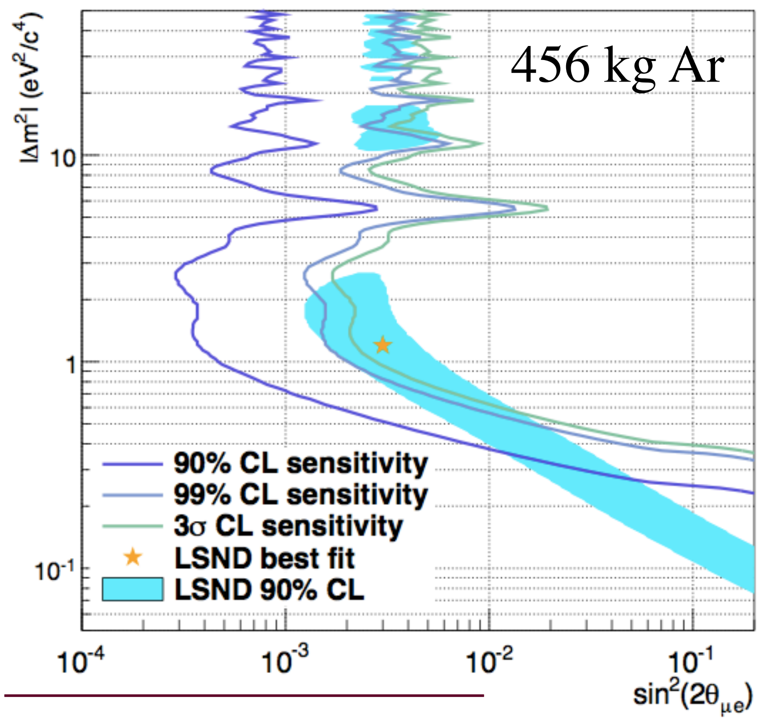
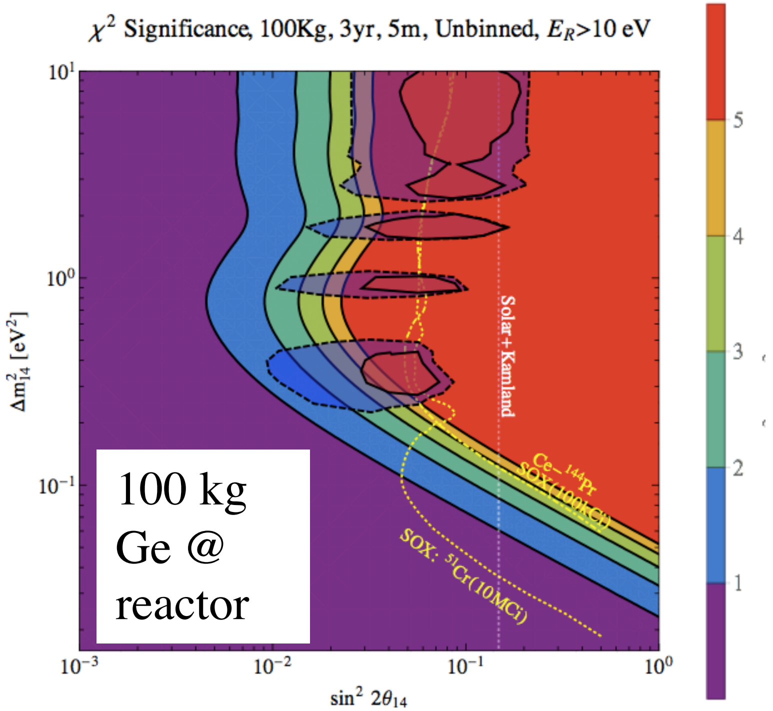
Physics Motivations for CEνNS

- Neutrino oscillations can use NC, flavor-blind CEνNS interaction to look for *L/E* shape distortions and disappearance

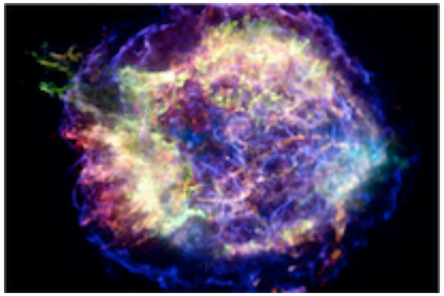


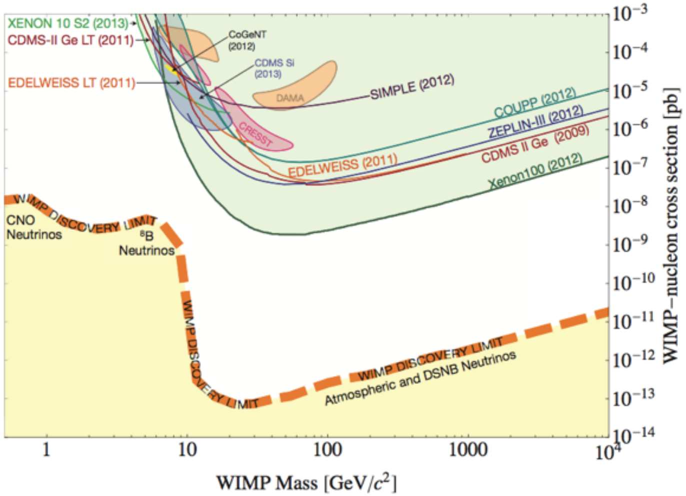


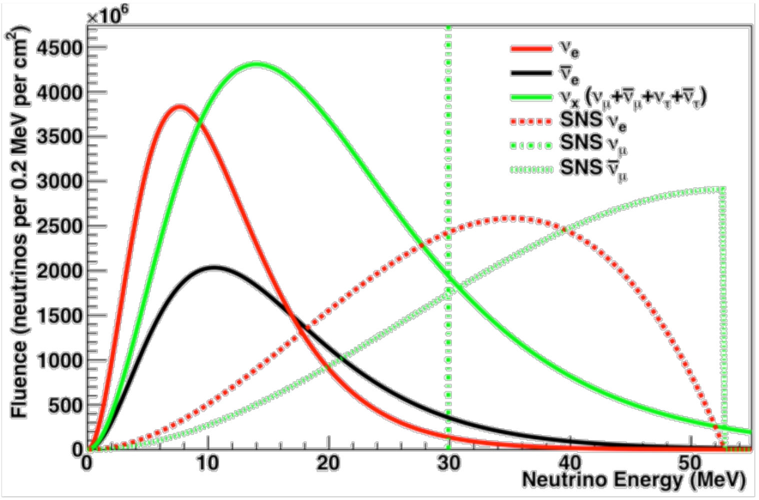
(Left Plot) A.J. Anderson et al., *Phys. Rev.* **D86** (2012) 013004. arXiv:1201.3805 [hep-ph].
(Right Plot) J. Dutta et al., arXiv:1511.02834 [hep-ph].

Physics Motivations for CEνNS

- CEνNS is irreducible background for deep underground WIMP Dark Matter searches
- Supernova cross sections (or direct detection) via CEνNS



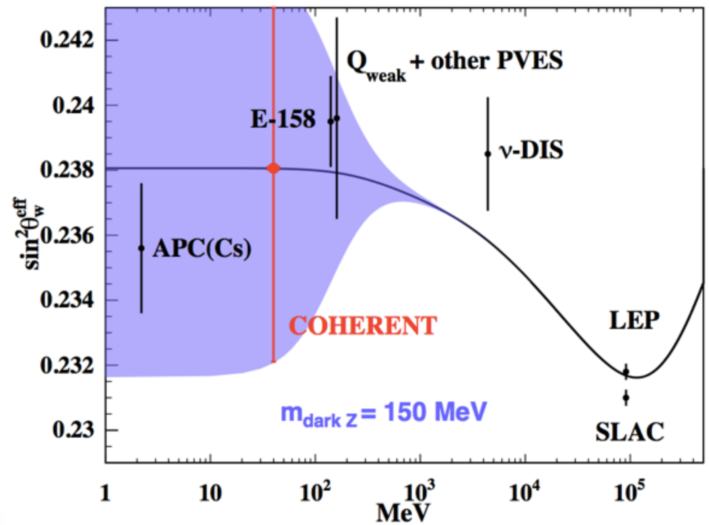


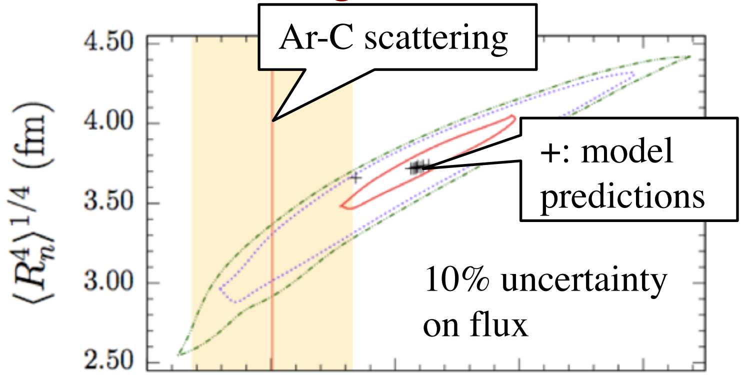


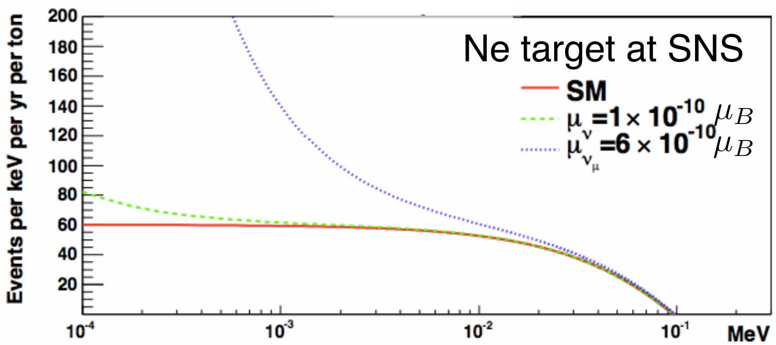
(Left Plot) J. Billard, E. Figueroa-Feliciano, L. Strigari. arXiv:1307.5458 [hep-ph].
(Right Plot) K. Scholberg, *Phys. Rev.* **D73** (2006) 033005. arXiv:hep-ex/0511042.
[1]A. Drukier and L. Stodolsky, *Phys. Rev.* **D30** (1984) 2295.

More Physics Motivations for CEνNS

- Method to measure $\sin^2 \theta_W$
- Neutrino magnetic moment distorts recoil spectrum
- Low-mass Dark Matter searches
- Nuclear physics form factors
- Nuclear safeguards







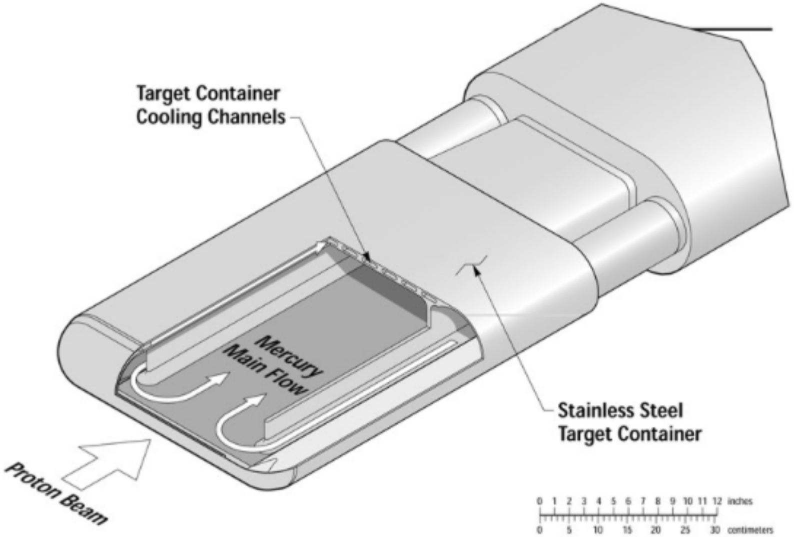
(Bottom-Left Plot) K. Patton et al., *Phys. Rev.* **C86** (2012) 024612 arXiv:1207.0693 [nucl-th].
(Bottom-Right Plot) Horowitz et al, *Phys. Rev.* **D86** (2012) 013004. arXiv:1201.3805 [hep-ph].

Neutrino Production at the SNS

- 0.9-1.3 GeV protons on liquid mercury target produces π^+
- Total power: 0.9–1.4 MW

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Pulsed at 60 Hz for ~400 ns → few × 10^{-4} duty (steady-state background reduction)
- 43 × 10^6 $\nu/cm^2/s$ 20 m at SNS maximum power (1.4 MW)



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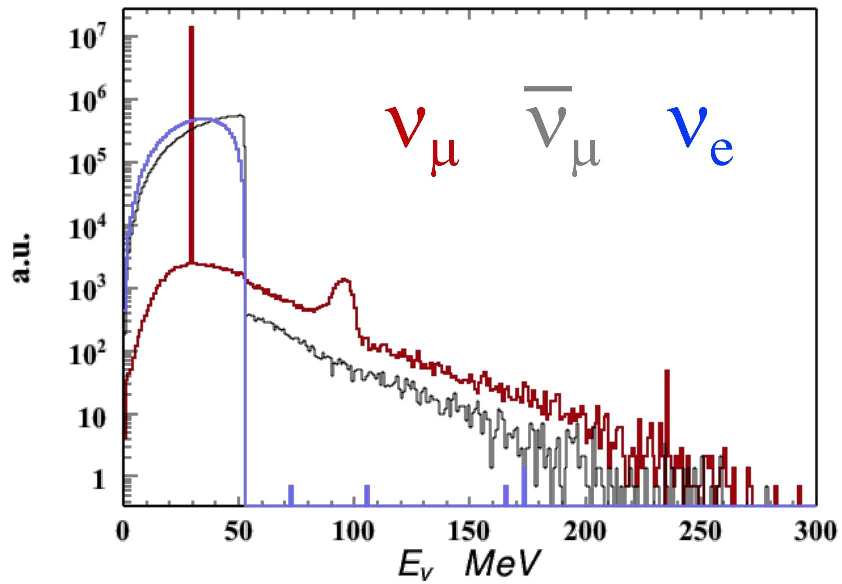
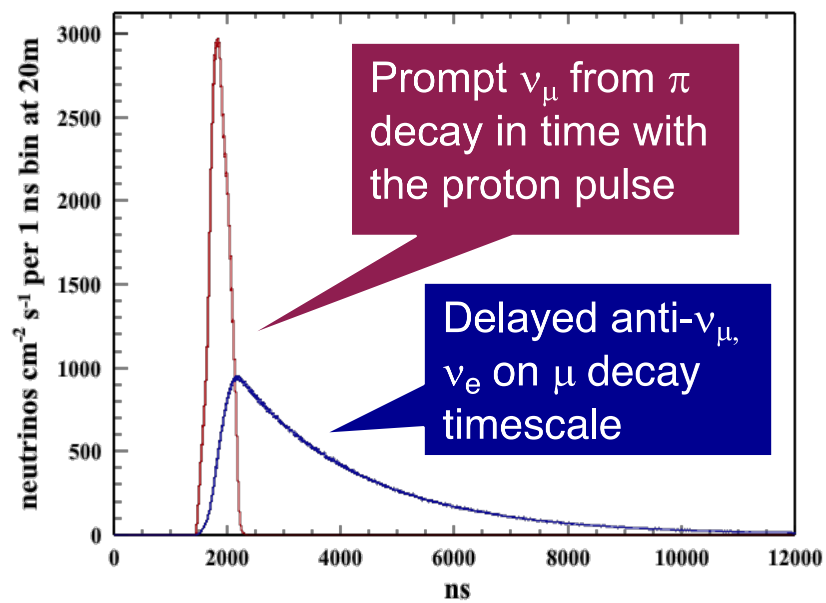
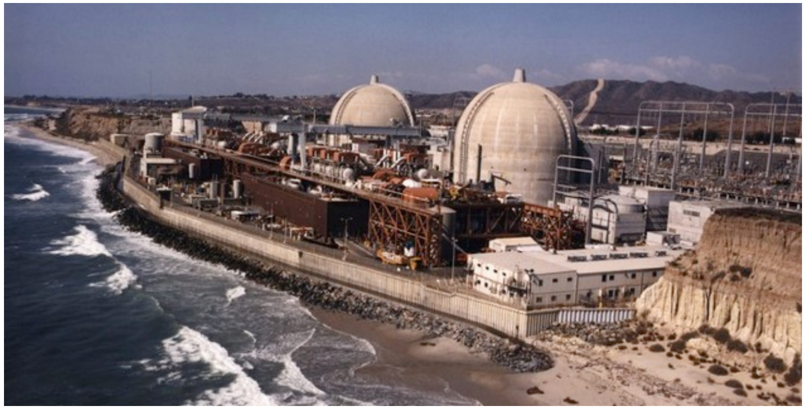
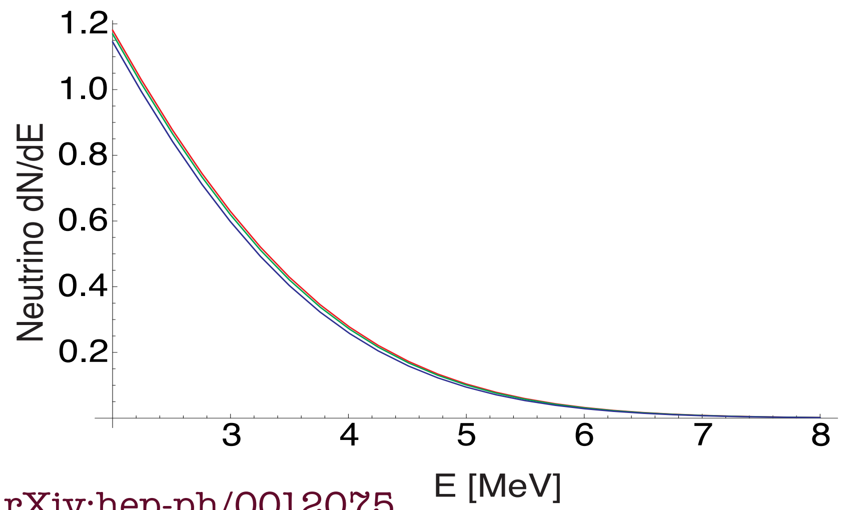




Aside: Why Not a Reactor?

- High flux of electron antineutrinos is very alluring ~10^{20}
- Energy spectrum is few-MeV
- Cross section goes as E_ν
- Recoil energy goes as E_ν^2
- No pulsing, just reactor on/off cycle to measure backgrounds





[1]H. Murayama & A. Pierce, *Phys. Rev.* **D65** (2002) 013012. arXiv:hep-ph/0012075.

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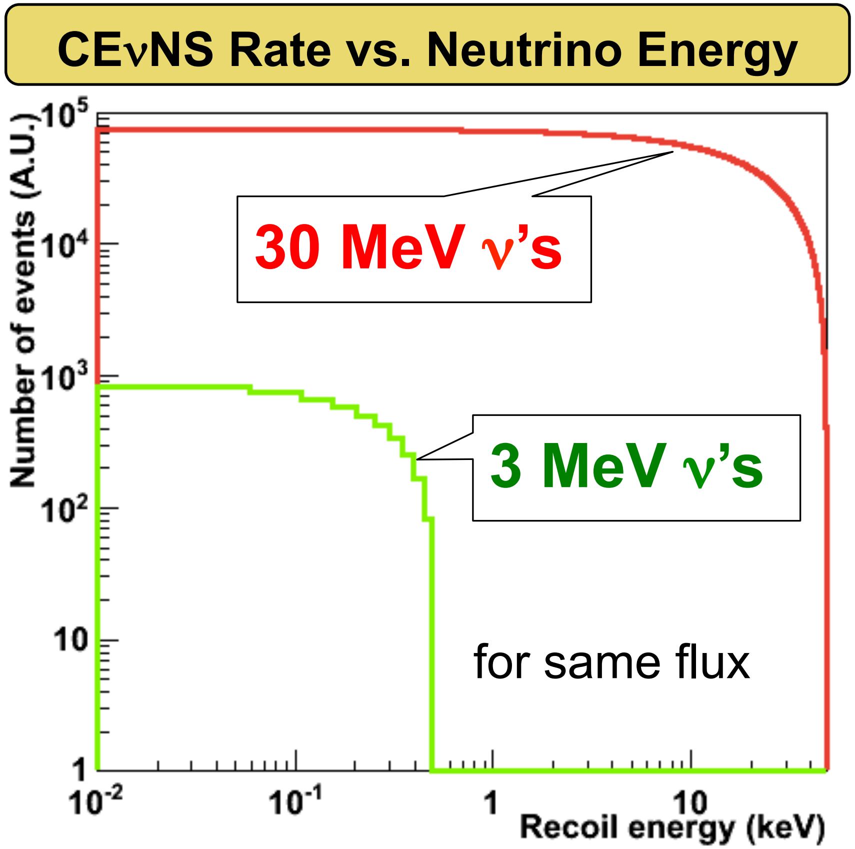

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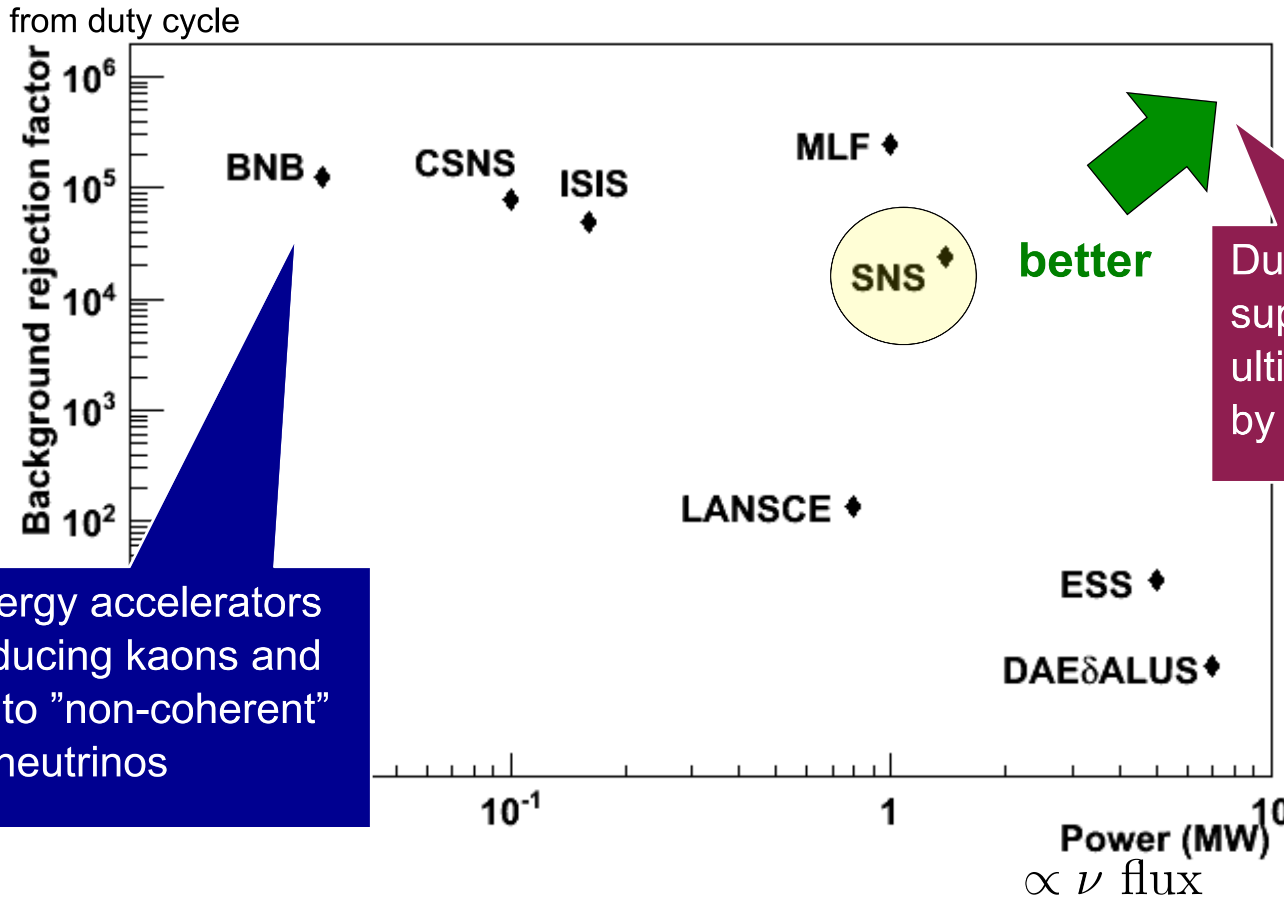
Comparing "Stopped" Pion Sources



Duty factor suppression is ultimately limited by muon lifetime

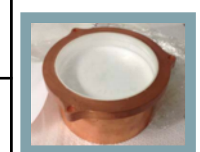
Higher energy accelerators begin producing kaons and this leads to "non-coherent" 236 MeV neutrinos

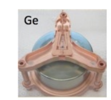
[1]Plot from K. Scholberg

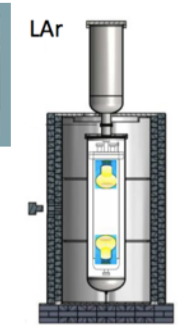
Physics Goals for COHERENT

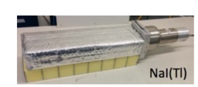
- Measure N^2 dependence across multiple targets
- Deploy detectors in low-neutron-background basement area
- Measure relevant neutrino-induced neutrons and quenching factors

Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVnr)	Data-taking start date; CEνNS detection goal
CsI[Na]	Scintillating Crystal	14	20	6.5	9/2015; 3σ in 2 yr
Ge	HPGe PPC	10	22	5	Fall 2016
LAr	Single-phase scintillation	35	29	20	Fall 2016
NaI[Tl]	Scintillating crystal	185* /2000	28	13	*high-threshold deployment started July 2016









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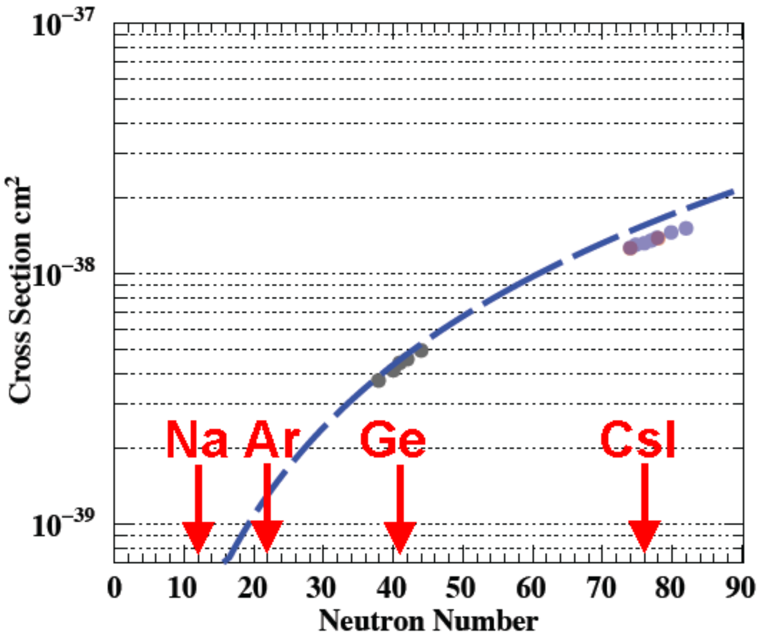
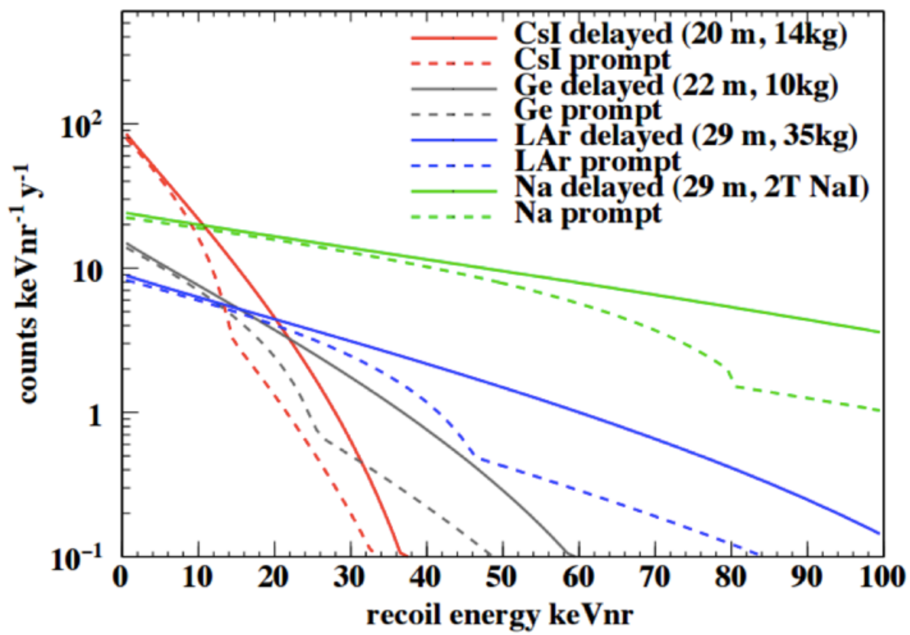
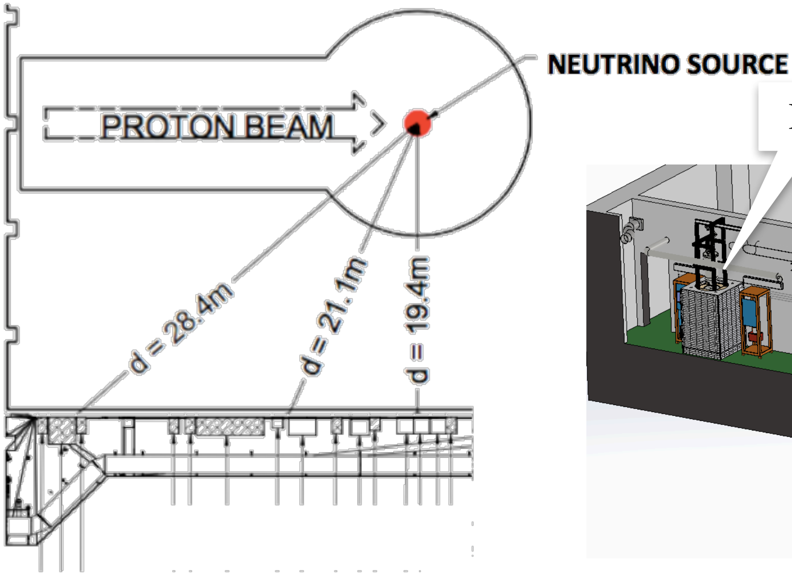
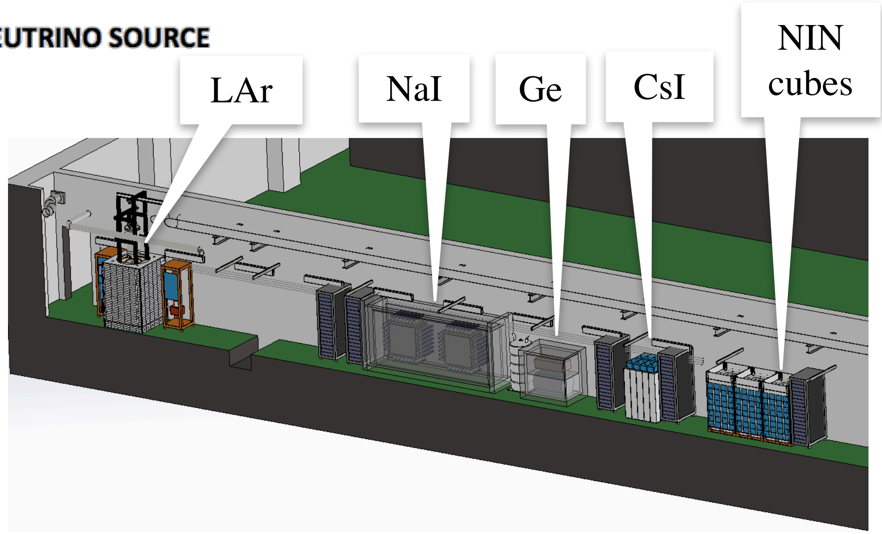




Neutrino "Alley"

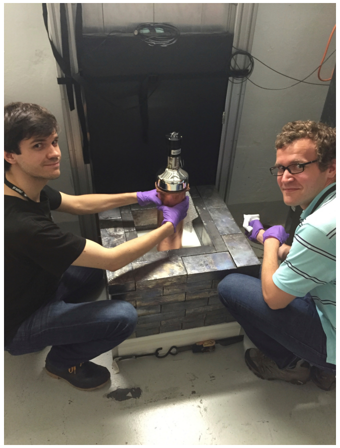
- Utility corridor has 22.5 m^2 for neutrino experiments and is largely decoupled from SNS operations; accessible via truck bay
- 1.5 m concrete floor supports large shielding structures
- 8 m.w.e. overburden and engineered backfill → neutron quiet
- 40 kW dedicated power install in October 2016

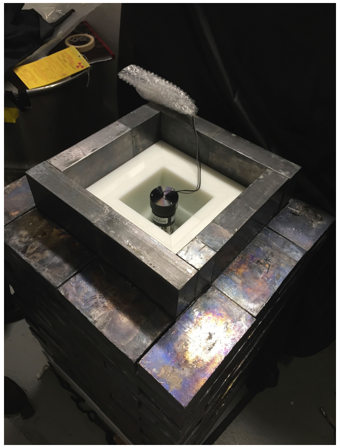


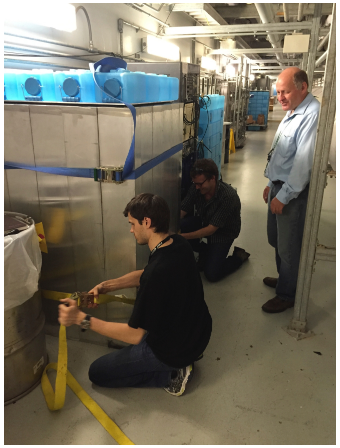


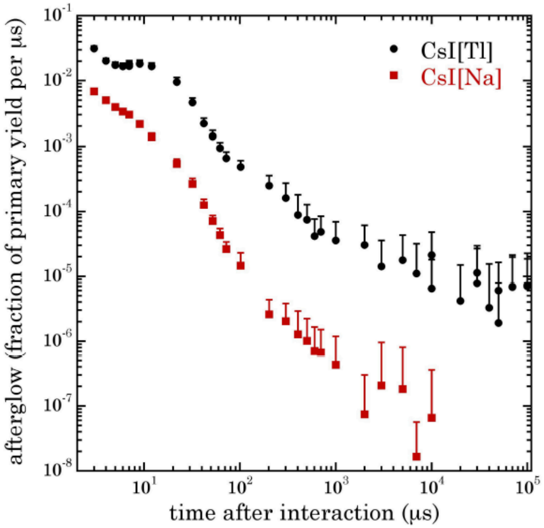
Detector Subsystems: CsI[Na]

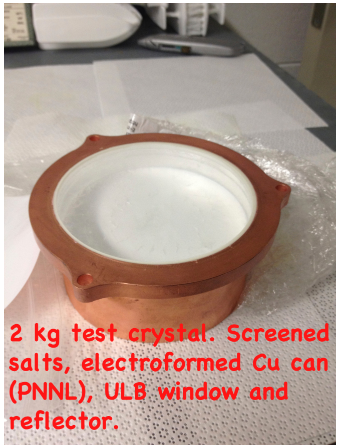
- Na doping reduces afterglow seen in common Tl doping
  - Tl doping insufficient for near-surface experiment
- Cs and I surround Xe in periodic table, very similar nuclear recoil response
- Statistical nuclear-/electron-recoil separation
- Quenching factors measured → 5 keVnr is easily achieved







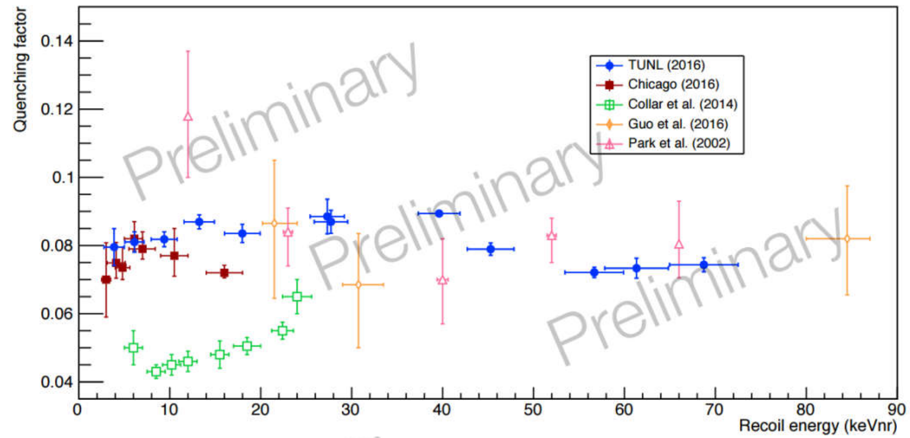


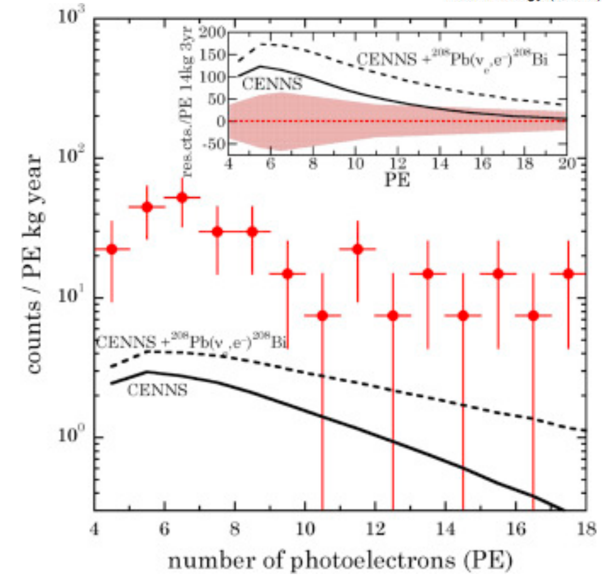


[1]J.I. Collar et al., *Nucl. Instrum. Meth.* **A773** (2015) 56.

Detector Subsystems: CsI[Na]

- 14 kg installed and running since July 2015 in neutrino alley
- Pb, water, and plastic shield
- Significant work on quenching factors has improved shows CEνNS is within reach
- Steady state backgrounds are 10-20% less at ORNL
- Neutrino-induced neutron backgrounds reduced to 4% with improved HDPE shield
- Results soon!





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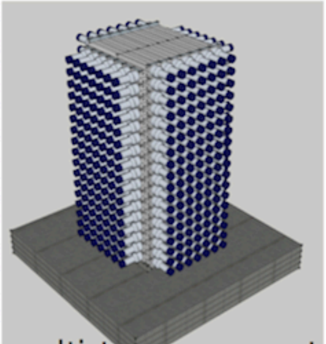
[1]J.I. Collar et al., *Nucl. Instrum. Meth.* **A773** (2015) 56.

Detector Subsystems: NaI[Tl]

- Born from discontinued DHS program; ~8 tons of NaI available
- 185 kg prototype for initial deployment
- 2 ton next phase deployment
- Up to 9 tons available
- NC CEνNS interaction
- Also CC interaction with ν_e
- https://twitter.com/NaIvE_SNS



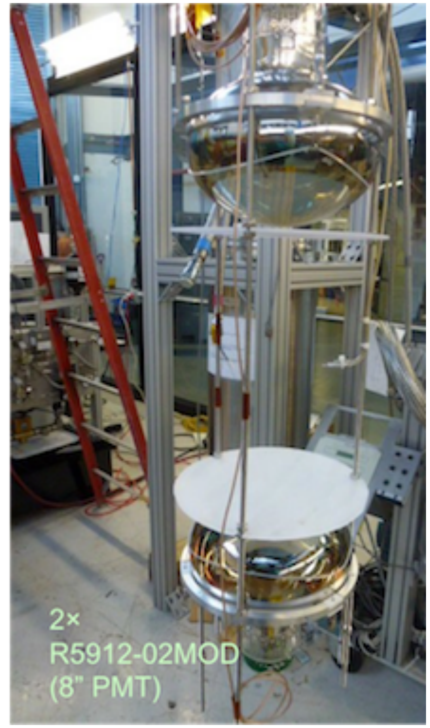
multi-ton concept

^{56}Fe	^{56}Fe$(\nu_e, e^-)^{56}$Co	Stopped π/μ	KARMEN	256 ± 108(stat) ± 43(sys)	264 [Shell] (Kolbe *et al.*, 1999a)
^{71}Ga	^{71}Ga$(\nu_e, e^-)^{71}$Ge	^{51}Cr source	GALLEX, ave.	0.0054 ± 0.0009(tot)	0.0058 [Shell] (Haxton, 1998)
		^{51}Cr	SAGE	0.0055 ± 0.0007(tot)	
		^{37}Ar source	SAGE	0.0055 ± 0.0006(tot)	0.0070 [Shell] (Bahcall, 1997)
^{127}I	^{127}I$(\nu_e, e^-)^{127}$Xe	Stopped π/μ	LSND	284 ± 91(stat) ± 25(sys)	210-310 [Quasi-particle] (Engel *et al.*, 1994)

[1] J.A. Formaggio and G. Zeller, *Rev. Mod. Phys.* **84** (2012) 1307.

Detector Subsystems: Liquid Argon

- Single-phase, scintillation only
- Built at FNAL by J. Yoo et al.
- 35-kg fiducial volume
- Readout is 2 × Hamamatsu R5912-02MOD PMT (8” cryogenic, high-gain)
- Excellent nuclear-/electron-recoil PSD demonstrated by miniCLEAN
- SCENE has measured quenching factors[1]
- ^{39}Ar helped by PSD and duty factor



[1]H. Cao et al., SCENE Collaboration, *Phys. Rev.* **D91** (2015) 092007. arXiv:1406.4825 [physics.ins-det].

Detector Subsystems: Liquid Argon

- Initial construction at Indiana University in Summer 2016
- Detector moved to SNS
- Construction is underway
- Running expected in December
- SNS run will contain shielding (inner layer to outer layer):
  - 23 cm water
  - ½” Cu
  - 4” Pb

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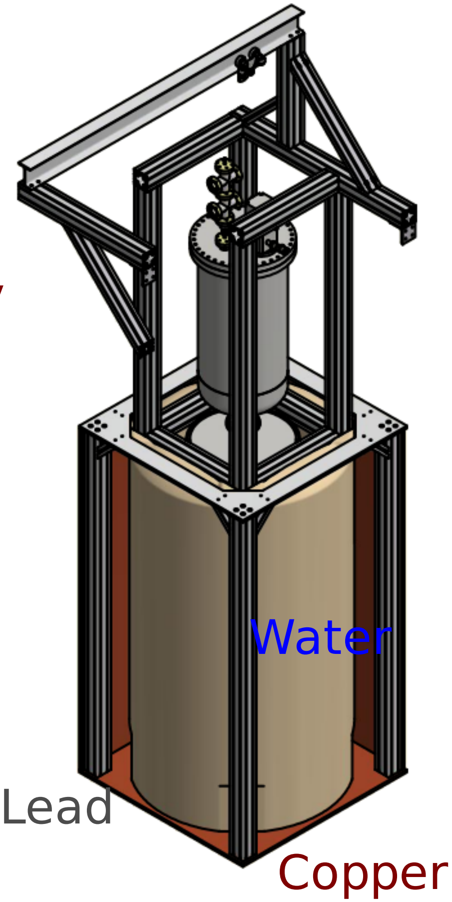

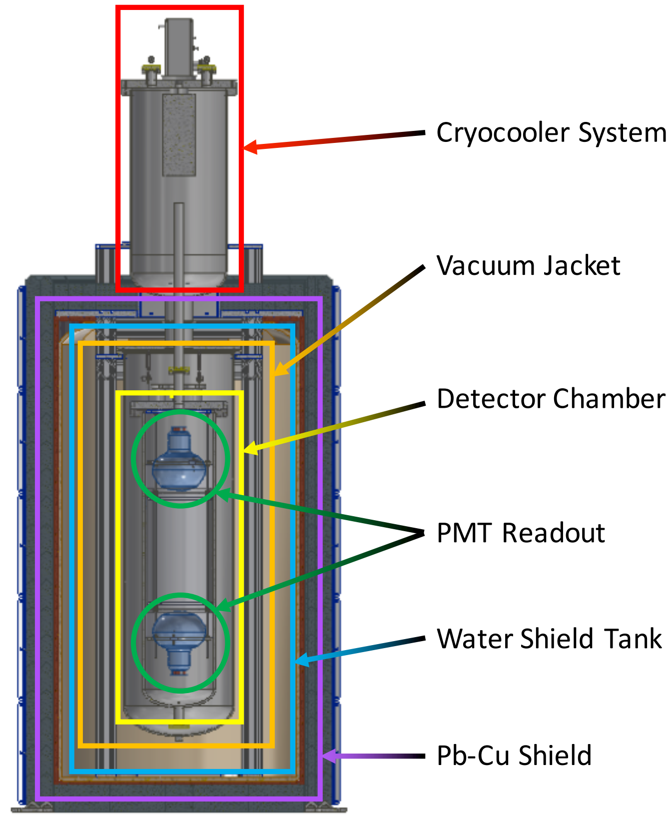

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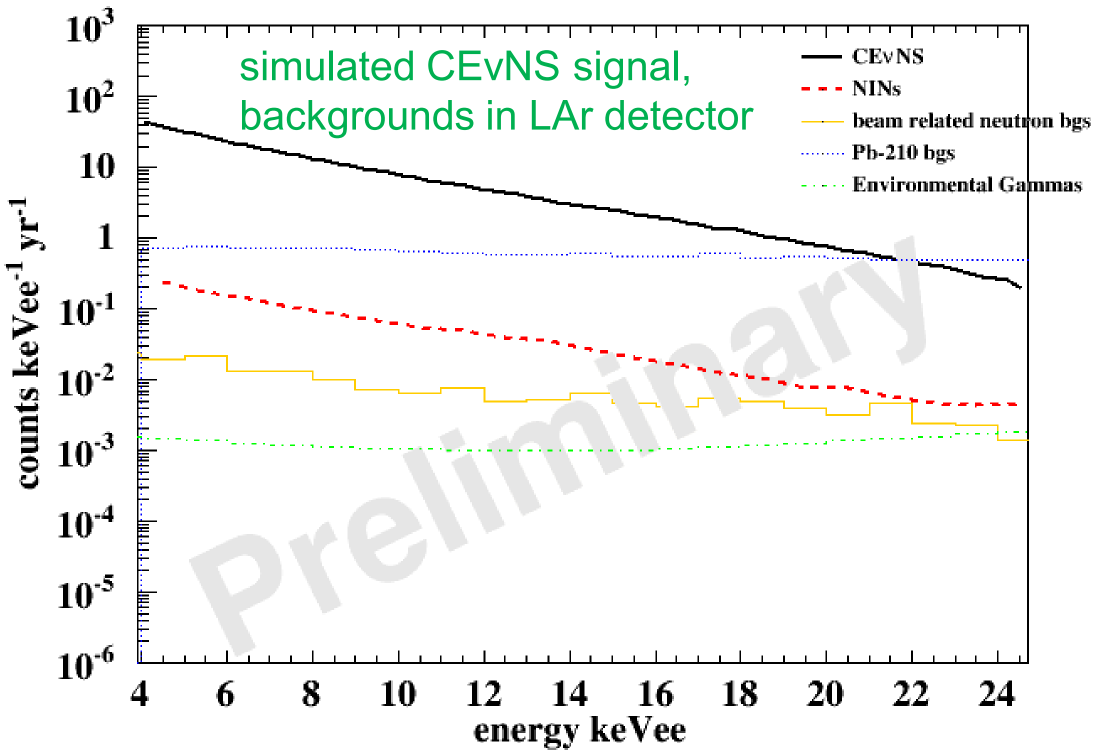
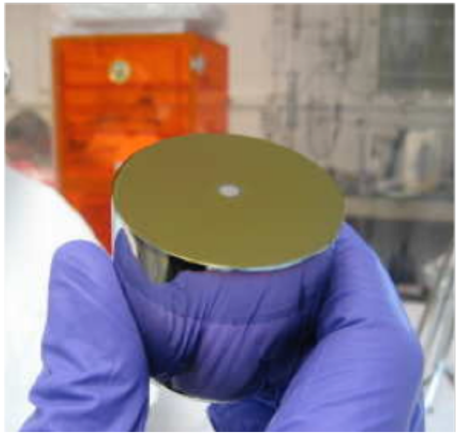
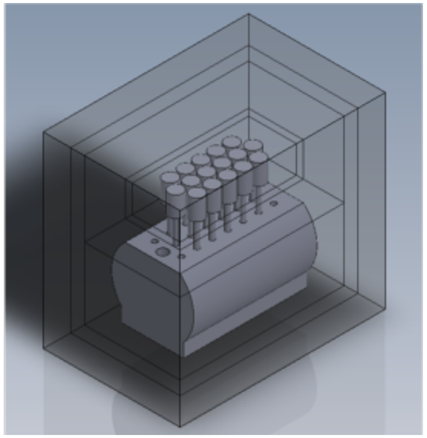
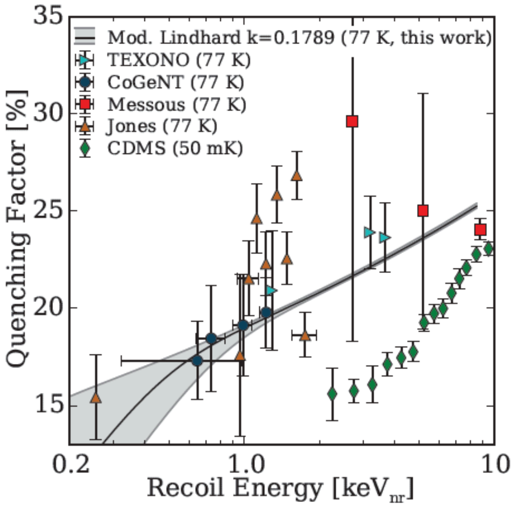


Detector Subsystems: Germanium

- HPGe PPC type that have excellent low-energy resolution and low threshold
- Repurposing of Majorana Demonstrator and LANL ^{nat}Ge detectors
- First phase is 5-10 kg of existing BeGe detectors in a copper, lead, and polyethylene shielding system
- Second phase could add more detector mass with larger (C4-style) detectors
- Quenching factors well known

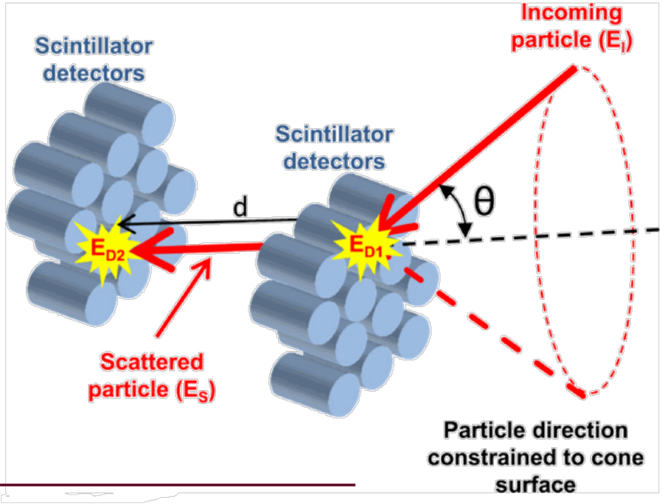






Neutron Backgrounds: Sandia NSC

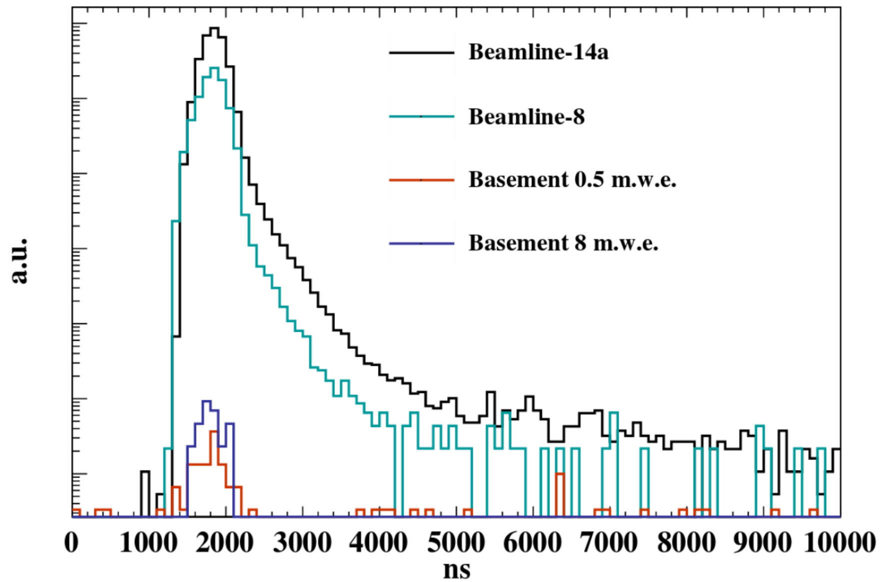
- Sandia Neutron Scatter Camera
- 2 Planes of EJ-309 neutron detectors (neutron/gamma PSD)
- Reconstruct neutron direction and energy
- Optimizable plane spacing

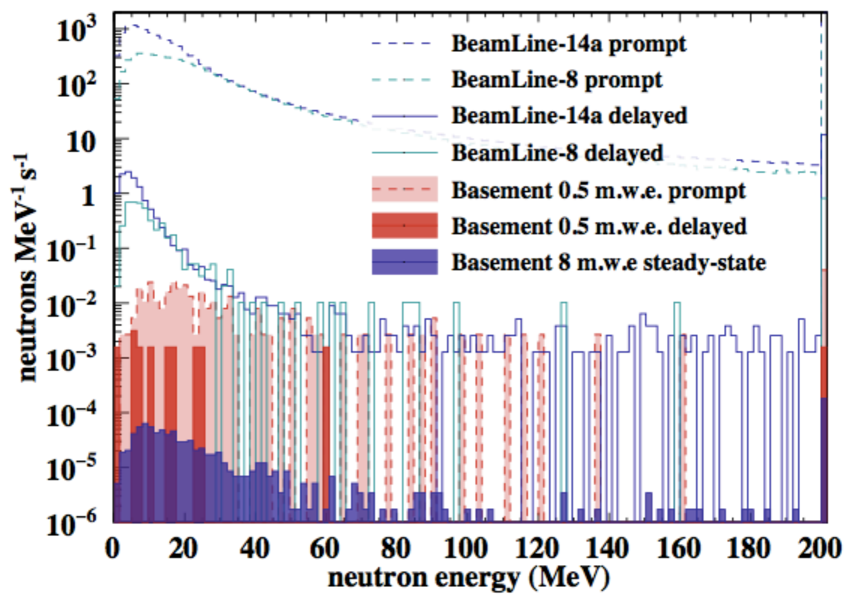


[1]N. Mascarenhas et al., *IEEE Trans. Nucl. Sci.* **56** (20109) 1269.

Neutron Backgrounds: Sandia NSC

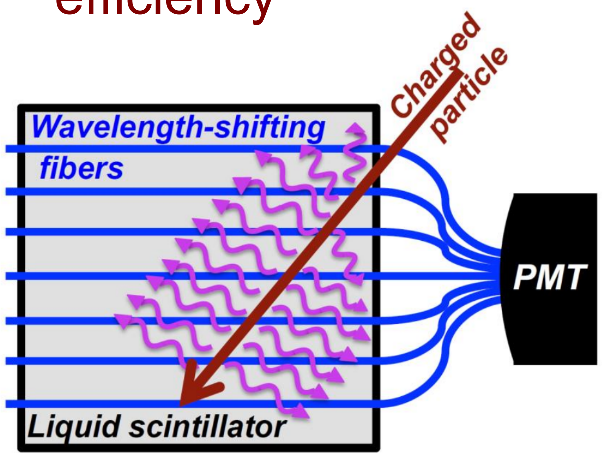
- Mapped neutrons across SNS
- Significant rate drop from guide hall to basement locations
- "Prompt" component visible
- "Delayed" neutrons in basement significantly suppressed

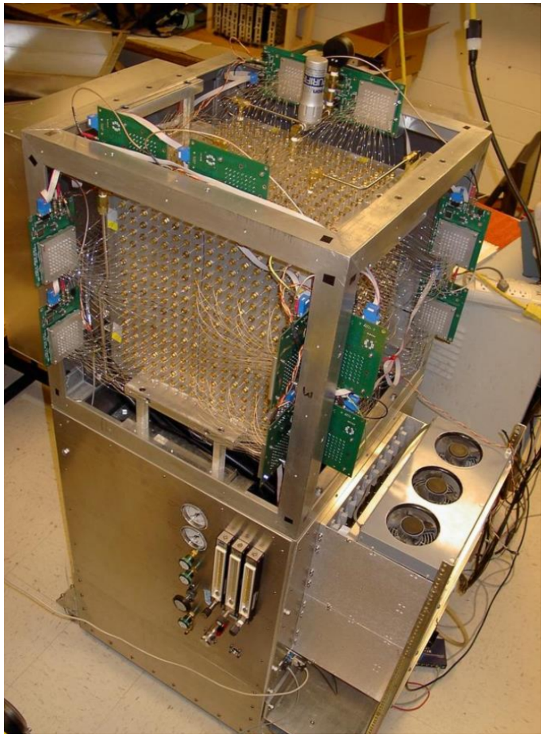


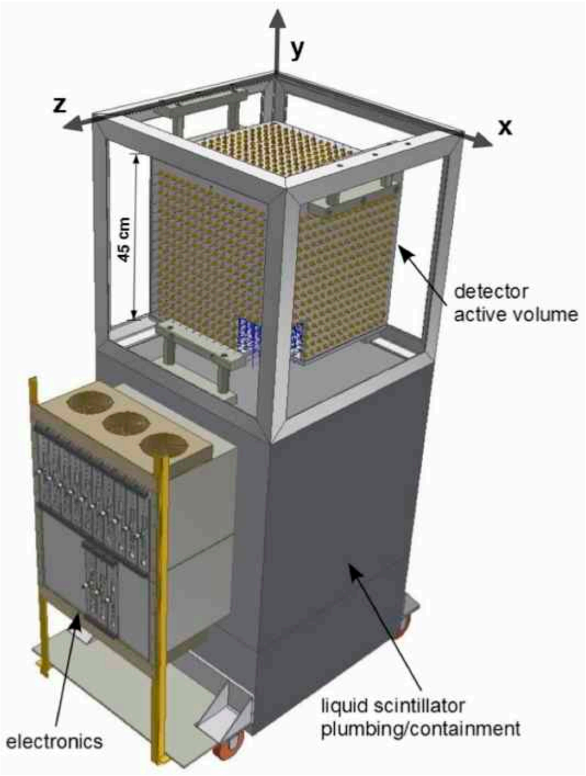


Neutron Backgrounds: SciBath

- 80 L liquid scintillator
  768 WLS fibers readout
  → event topology
- No optical separation and uniform tracking efficiency



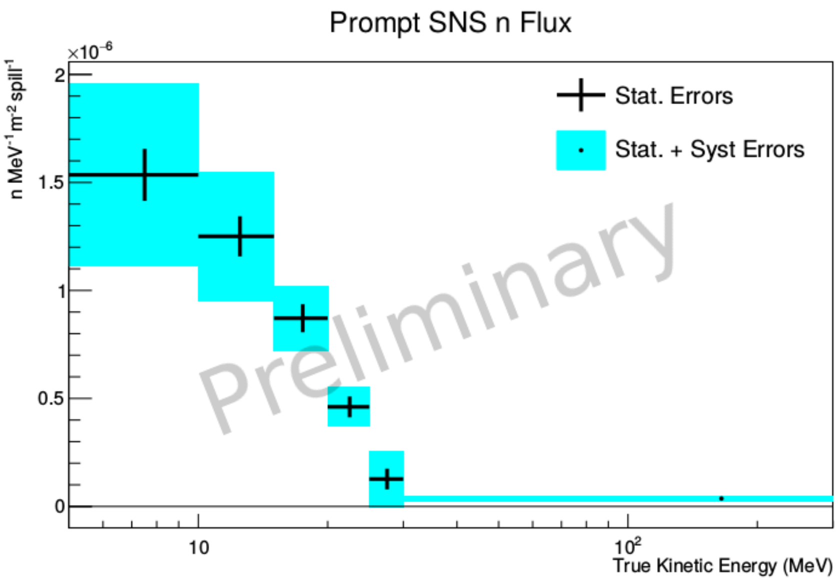


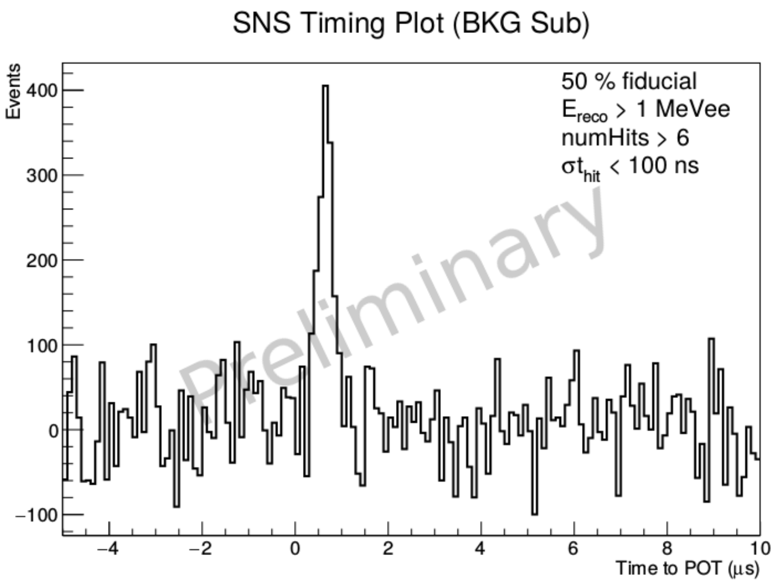


[1]R. Tayloe, *Nucl. Instrum. Meth.* **A562** (2006) 198.

Neutron Backgrounds: SciBath

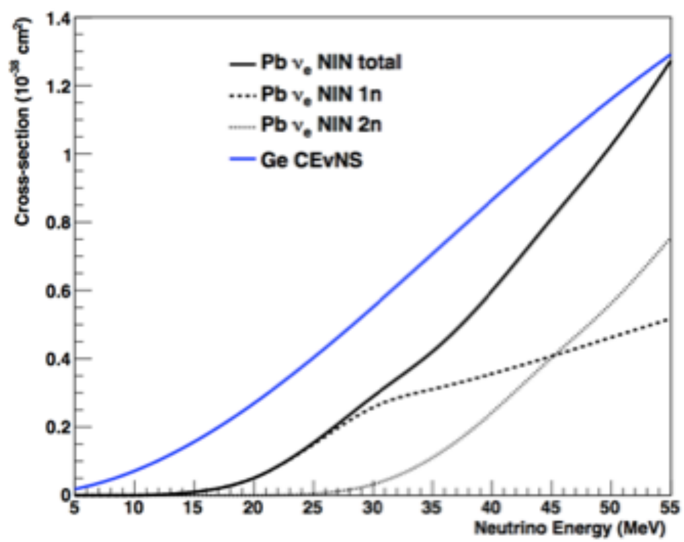
- Measured at LAr site in SNS Neutrino Alley
- **Prompt flux (5-30 MeV)** → $(2.1 \pm 0.4) \times 10^{-5}$ m^{-2} μs^{-1} MW^{-1}
- Delayed flux → $(1.9 \pm 0.7) \times 10^{-5}$ m^{-2} μs^{-1} MW^{-1}
- Fluka transport neutrons → (3.2 ± 0.3) in ROI per year (prompt)

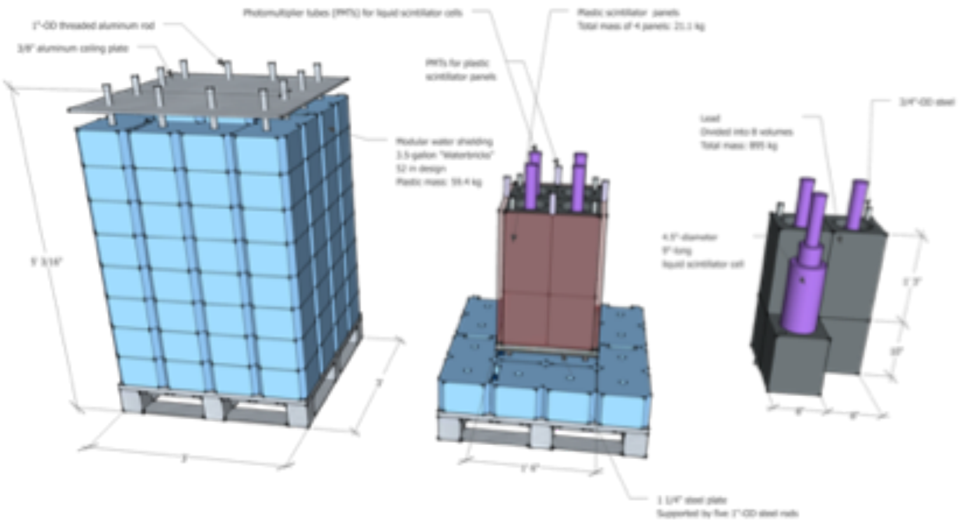




Neutrino Induced Neutrons (NINs)

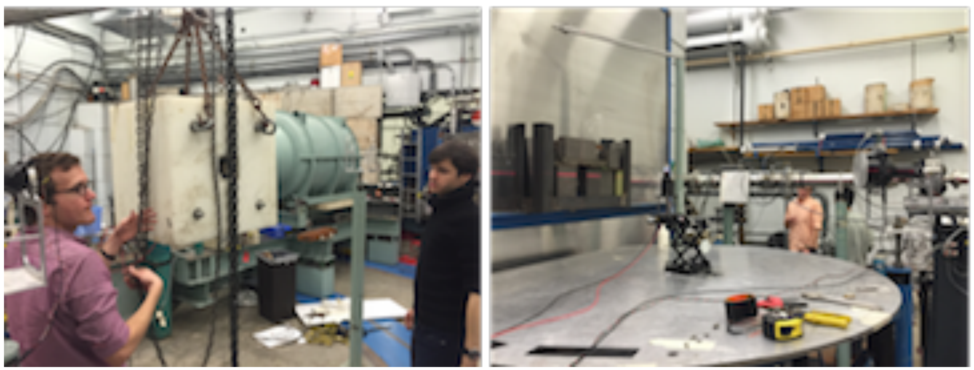
- Pb shielding interacts with ν_e and can break-up to 1 n or 2 n
- Shield can give CEνNS backgrounds
- "Neutrino Cubes" testing neutron production from Pb, Fe inside water shield
- https://twitter.com/theLeadNube



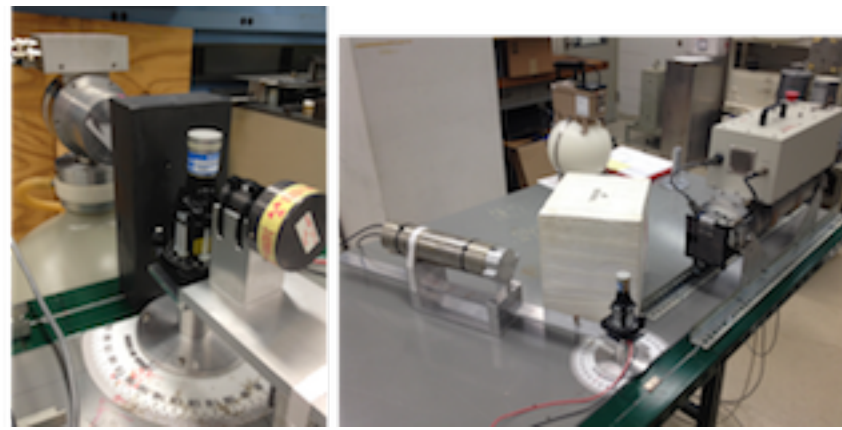


Quenching Measurements

- Chicago has used commercial D-D neutron generator
- Duke group at TUNL have created a tunable p-^{7}Li and D-D neutron sources to test low-energy nuclear recoils for quenching factor measurements



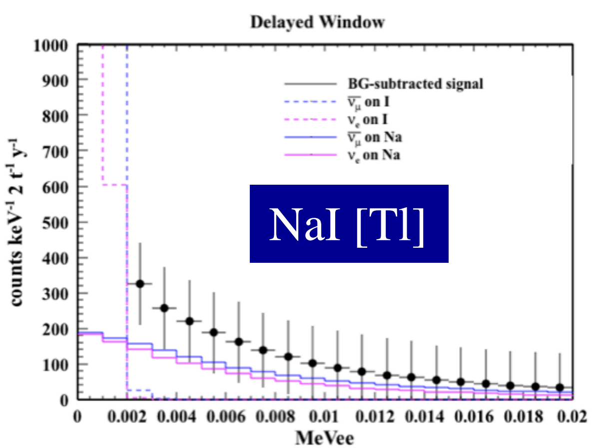
TUNL Setup

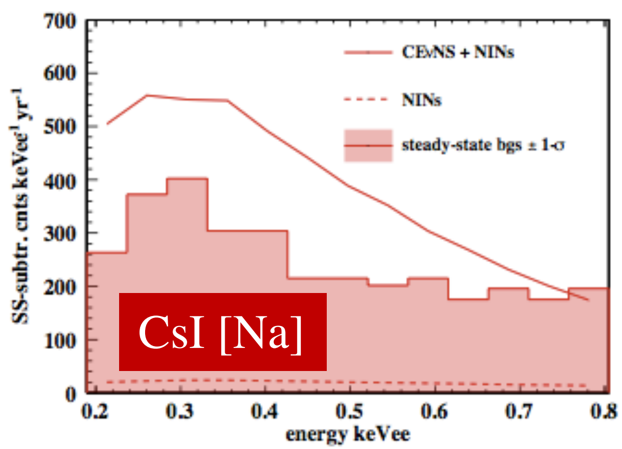


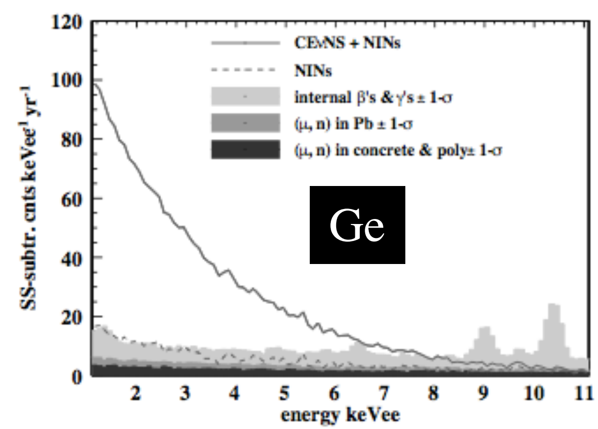
Chicago Setup

Conclusions

- COHERENT is deploying a suite of detector technologies in the neutron-quiet SNS basement
- First light measurement to test N^2 dependence
- Sensitivities shown below (LAr is being completed)
- LAr expects ~300/700 events on ~100/900 steady-state backgrounds in a year in prompt/delayed region







The COHERENT collaboration

arXiv:1509.08702

Institution	Board Member
University of California, Berkeley	Kai Vetter
University of Chicago	Juan Collar
Duke University	Kate Scholberg
University of Florida	Heather Ray
Indiana University	Rex Tayloe
Institute for Theoretical and Experimental Physics, Moscow	Dmitri Akimov
Lawrence Berkeley National Laboratory	Ren Cooper
Los Alamos National Laboratory	Steve Elliott
National Research Nuclear University MEPhI	Alex Bolozdynya
New Mexico State University	Robert Cooper
North Carolina Central University	Diane Markoff
North Carolina State University	Matt Green
Oak Ridge National Laboratory	Jason Newby
Sandia National Laboratories	David Reyna
University of Tennessee, Knoxville	Yuri Efremenko
Triangle Universities Nuclear Laboratory	Phil Barbeau
University of Washington	Jason Detwiler

- Collaboration: ~65 members, 16 institutions (USA+ Russia)